BACKGROUND OF THE INVENTION

The present invention relates to imaging through a random medium such as the turbulent atmosphere or the slowly changing optics of a camera; and how to combat the deleterious effects of that medium, in a real-time and an automatic way. We show how to determine the distorting wavefront caused by the medium and how to control an adaptive optic in the optical system to eliminate that wavefront.

Diversity imaging uses one or more of the images, each with a known diversity (phase, wavelength, or spatial shift), to deduce both the unknown object and the parameters of the medium. Gonsalves and Devaney held the first patent of this kind and the method was used by Gonsalves and others to deduce the flaw in the Hubble Space Telescope. In the usual embodiment of this method the diversity is a quadratic phase shift, which can be introduced by defocusing the optical system. Love, et al., Duncan, et. al., and Paxman hold current patents which use phase diversity.

Unlike the patents by Gonsalves and others, this invention uses only the measured image sequence, itself, as data. No additional image, such as a second, defocused image is required. Successive images form the multiplicity of images required for diversity imaging and the changes to the adaptive optic are the diversities.

This novel approach eliminates the need for any other mechanisms. It applies to any adaptive optic and to any digital camera. The innovations are the use of sequential images as the diversity images and the use of a sequential diversity processor to control the adaptive optic.

Further background references are listed below:

References

1. R. W. Gerchberg and W. O. Saxon, "Phase Determination from Image and Diffraction Plane Pictures", Optic. 34, 275 (1971).
2. R. Gonsalves, "Phase Retrieval from Modulus Data", J. Opt. Soc. of Am, 66, 961 (1976).
3. J. Fienup, "Phase retrieval algorithms: a comparison," Ap. Opt., 21, 2758 (1982)
4. R. Gonsalves, "Phase Retrieval and Diversity in Adaptive Optics", Opt. Eng., 21, 829 (1982)
5. B. Ellerbroek and D. Morrison, "Linear methods in phase retrieval," SPIE Proc. 351, 90 (1982).
6. M. Teague, "Deterministic phase retrieval: a Green's function solution," J. Opt. Soc. of Am. 73, 1434 (1983).
7. R. Gonsalves, "Phase Retrieval by Differential Intensity Measurements", J. Opt. Soc. of Am A, 4, 166 (1987).
8. R. Paxman and J. Fienup, "Optical misalignment sensing and image reconstruction using phase diversity," J. Opt. Soc. of America, A 5, 914 (1988)
9. F. Roddier et al., "A Simple Low-Order Adaptive Optics System For Near-Infrared Applications", Publications of the Astronomical Society of the Pacific, 103, 131 (1991).
10. J. E. Graves et al., "The University of Hawaii adaptive optics system: III The Wavefront Curvature Sensor", SPIE Proc., 1542, 262 (1991).
11. R. Kendrick, D. Acton, A. Duncan, 'Phase-diversity wave-front sensor for imaging systems," Apl. Opt. 33, 6533 (1994).
12. M. A. Voronstov and V. P. Sivokon, " Stochastic parallel-gradient-descent technique for high-resolution wave-front phase-distortion correction," J. Opt. Soc. Am. A, 15, 2745 (1988).

BRIEF DESCRIPTION OF THE DRAWINGS:

Fig. 1 is a combined block-pictorial representation of an imaging system which uses an adaptive optic and a sequential diversity processor, in accordance with the invention.

Fig. 2 is a block diagram of the sequential diversity processor, showing the input images from a detector and the output control signals for the adaptive optic.

Fig. 3 shows a computer simulation of the invention as it would apply to the imaging of a point source, like a star, imaged through a turbulent atmosphere.
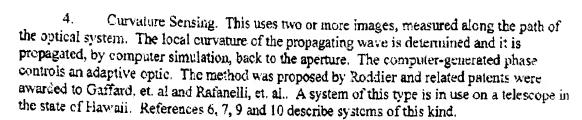
DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The detector seen in both Fig. 1 and in Fig. 2 is one in which the picture is captured as discrete picture elements - essentially, a digital camera. We propose no new detecting mechanism for the camera; digital cameras exist and are improving in sensitivity and resolution at a dramatic pace.

The adaptive optic (AO) shown in both Fig. 1 and in Fig. 2 is a high-resolution device which allow a wide range of correction mechanisms, such as Zernike polynomial fitting of a complicated wavefront. It is similar to the sophisticated systems currently installed on national telescopes and it has capabilities well beyond the automatic focussing and registration mechanisms in consumer camcorders. These sophisticated AO systems improve image quality by about a factor of ten. They will almost certainly appear in consumer products, after the cost of adaptive optics decrease and after simple, real-time control mechanisms are invented.

The AO in these figures is used to cancel the wavefront distortion, W. Thus, to be effective, the optical system of Fig. 1 must sense the wavefront. There are five well-known mechanisms for wavefront sensing, which we review here. The five are as follows:

1. Dithering. This method continuously changes the adaptive optic and monitors the image quality of the observed image. The method was patented by O'Meara, who made slowly varying changes to each channel of the adaptive optic, modulated each channel, demodulated the image quality in each channel, and controlled the adaptive optic with the set of image qualities. A recent improvement, stochastic parallel-gradient-descent, has been proposed by Voronstov and Sivokon (Reference 12). They make random changes in all channels and, over time, determine which average changes improve the image quality.

2. Shearing Interferometer. This method uses a reference beam to create an interference pattern which describes the unknown wavefront. Hardy was the first to patent a wavefront sensor based on this device. It has been used successfully in several astronomical installations. Its major drawback is the extra measuring equipment, including a laser-based interferometer, that has to be installed.

3. Shack-Hartmann Sensor. This device uses an array of lenses to image small sections of the wavefront onto a detector. Shifts in the small images are caused by local tilts in the waveform. From these tilts one reconstructs the wavefront. Feinleib held the first patent. A major drawback is the requirement for the lenslet array and sensors.

4.	Curvature Sensing. This uses two or more images, measured along the path of the optical system. The local curvature of the propagating wave is determined and it is propagated, by computer simulation, back to the aperture. The computer-generated phase controls an adaptive optic. The method was proposed by Roddier and related patents were awarded to Gaffard, et. al and Rafanelli, et. al.. A system of this type is in use on a telescope in the state of Hawaii. References 6, 7, 9 and 10 describe systems of this kind.

5.	Phase retrieval and diversity. Our invention is similar to these, in that they use digital imagery, an adaptive optic, and multiple images. The method was first suggested by Gonsalves (Reference 2). References 1-5, 8 and 11 use phase retrieval and/or diversity.

Many inventors have tried to use post-processing of a series of images to enhance the composite. Patents to Rhodes fall into this category. While such techniques may be useful if the data are already captured and no adaptive optic was available during measurement, this inventor teaches, " If you want a good picture, take a good picture." This implies that it is far better to improve the image in its taking than to try to improve the image by computer processing, after the fact.

Referring to Fig. 1 and Fig. 2, we use the following notation:

$W(k)$	=	Unknown distorting wavefront at time k.

$T(k)$	=	Phase put on the AO at time k.

$C(k)$	=	Compensated phase to be estimated by a diversity algorithm

	=	$W(k) + T(k)$.	(1)

$I(k)$	=	Measured image at time k.

$D(k)$	=	Diversity phase.

We consider a diversity algorithm where $I(k-1)$ is the first image and $I(k)$ is the diversity image. With this convention the diversity phase is the change in the AO phase from time k-1 to time k. Thus,

$$D(k) = T(k) - T(k-1) .\qquad(2)$$

The phase diversity algorithm is set up to estimate $C(k)$, the compensated phase at time k. Call the estimate $Q(k)$. $Q(k)$ is, from equation (1),

$$Q(k) = W1(k) + T(k) ,\qquad(3)$$

where $W1(k)$ is an estimate of $W(k)$, the unknown phase at time k. (We know $T(k)$, so it need not be estimated.) At time k + 1 we would like to set the AO phase to the negative of the unknown wavefront at time k+1. We do not know W at time k+1 but we do have an estimate

of the wavefront at time k, namely, $W1(k)$. This will be a good estimate of $W(k+1)$ if AO updates are well within the time constant of the changing medium. Thus. we set

$$T(k+1) = -W1(k) , \qquad (4)$$

which will tend to cancel the wavefront distortion at k+1.

Solving (3) for $W1(k)$ and substituting it into (4), we have

$$T(k+1) = -Q(k) +T(k) ,$$

which implies

$$T(k) = -Q(k-1) + T(k-1) . \qquad (5)$$

Turning to the diversity phase, we put (5) into (2) to get

$$D(k) = (-Q(k-1) + T(k-1)) - T(k-1)$$

$$= -Q(k-1) . \qquad (6)$$

This is the specification for the diversity phase at time k.

Finally, we put (6) into (5) to get a new expression for the AO phase:

$$T(k) = T(k-1) + D(k) . \qquad (7)$$

Equations (6) and (7) give us the recipe we sought. The AO phase, $T(k)$, is the previous AO phase plus the diversity phase, $D(k)$; and the diversity phase is the negative of the diversity algorithm's output at time k-1.

These equations are expressed in block diagram form in Fig. 2. The inputs to the diversity algorithm are images $I(k-1)$ and $I(k)$; the output is $Q(k)$, an estimate of the compensated phase; the phase diversity is $D(k)$; and a feedback loop calculates $T(k)$.

Fig. 3 shows a computer simulation of 24 cycles of the sequential diversity imager. The object is a point source, such as a star. The first observed image of the star is in the lower left of Fig 3. The compensated image is directly above. The last pair is in the upper right. The lower rows show how the star "twinkles" over time. Each uncompensated image is called a speckle pattern and is characteristic of a star imaged through the earth's atmosphere.

A measure of the image quality is the Strehl ratio, i. e., the peak value of the aberrated star image to the peak value of an unabberated star image. Higher Strehl ratio means higher image quality. For the 24 images shown, the average Strehl ratio is 0.045.

The sequential diversity imaging technique produced the images shown directly above each twinkling image. The average Strehl ratio for the compensated images is 0.467. This is an improvement of about a factor of 10.

We note that in our simulation the time constant of the atmospheric disturbance is about eight images; that is, the star image takes about eight cycles to appear completely uncorrelated with its earlier image. Thus the cycle time of the imager is, in this simulation, eight times shorter than the time cycle of the atmosphere. The latter is quite variable, but a reasonable estimate is 8 milliseconds. Thus, the sequential processor must measure the new image and calculate the new AO settings in about one millisecond.

When we doubled the atmospheric time constant to 16 ms, the average Strehl ratio of the imager improved to 0.65, an increase of about 14 in the image quality, over the uncompensated star images. When we halved the atmospheric time constant to 4 ms, the average Strehl ratio improved only to 0.29, an increase in image quality of a factor of about 6.

Finally, we allowed the atmospheric time constant to vary from 2 to 16 ms over the 24-image sequence and the average quality factor still improved - by a factor of 7.5. More significantly, when the time constant time was very small and the processor was unable to keep up with the rapidly changing atmosphere, it nonetheless recovered, without catastrophic failure. That is, the processor is self-correcting.